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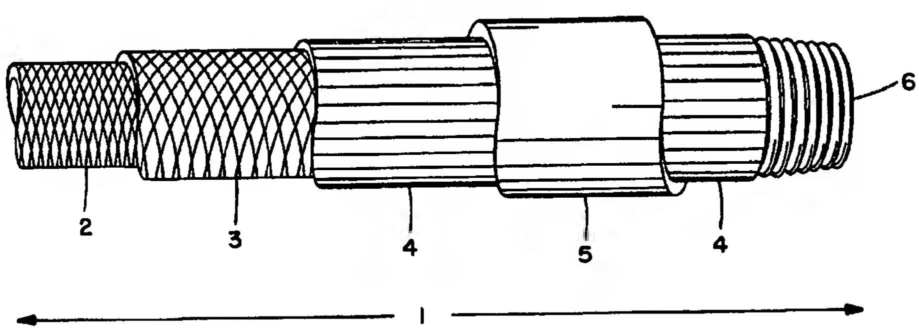
(54) Title: COMPOSITE PIPE STRUCTURES HAVING HIGH CONTAINMENT AND AXIAL STRENGTH



(57) Abstract

Composite laminated fiber reinforced plastic pipe (1) having improved resistance to micro-cracking and delamination is disclosed. The pipe is composed of a plurality of laminated layers (2, 3, 4) forming the pipe wall structure, including an outer axial bearing layer containing reinforcing continuous fibers (5) embedded in a thermoset resin binder and disposed at an angle of 0° up to +/- 30° with respect to the longitudinal pipe axis and an inner layer in contact with the inner surface of the outer layer in containing reinforcing continuous fibers embedded in a thermoset resin binder and disposed at an angle of greater than +/- 30° with respect to the longitudinal pipe axis.

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COMPOSITE PIPE STRUCTURES HAVING HIGH CONTAINMENT AND AXIAL STRENGTH

BACKGROUND OF THE INVENTION

Field of the Invention

The invention relates to pipes and tubing having a wall structure composed of fiber reinforced polymer composite laminates.

Description of Related Art

Fiber reinforced plastic pipe (FRP pipe) is finding increased usage as piping in chemical plants as well as casing used in the drilling of oil and gas wells and casing and tubing for the transport of crude oil and natural gas up from the well source.

The advantage of FRP pipe over carbon steel pipe in oil/gas applications includes superior corrosion resistance, flexibility in achieving mechanical property design targets and improved fatigue resistance. FRP pipes are also of considerably lighter weight for a given wall thickness than their steel pipe counterparts.

FRP pipe designed for use in high pressure piping or casing such as crude oil pipelines and oil well tubing are generally prepared by impregnating a roving of filaments of a high strength material, such as continuous glass filaments, with a thermosettable resin composition, such as an epoxy resin, and winding the impregnated filaments back and forth onto a mandrel under tension to form a plurality of intermeshed filament windings. Filaments may be wound at an angle of 90° to the pipe axis or at angles of 0° to plus and minus about 90° (+/- 90°) with

respect to the pipe axis. A helical filament winding pattern is formed when the winding angle is between 0° and 90° with respect to the longitudinal pipe axis. After a desired pipe wall thickness is achieved, the winding operation is discontinued, the resin is cured and the mandrel is extracted resulting in a cylindrical pipe having a fiber reinforced wall structure. FRP pipes of this type and their method of production are disclosed, e.g., in U.S. Patents 2,843,153 and 5,330,807, the complete disclosures of which patents are incorporated herein by reference.

FRP pipe designed for use in onshore or offshore fossil fuel recovery must be constructed to withstand two basic forces to which it will be subjected. The first force is an outer radial load exerted along a vector normal to the pipe walls by fluids (oil or drilling muds) which are conveyed under moderate to high pressure through the pipe, also known as the hoop load. The second force is an axial tensile load exerted along vectors parallel to the pipe axis and occasioned by the fluid pressure and/or the weight of a long string of coupled pipe sections suspended in the ground at the well bore and/or between the well bore and surface platform in offshore recovery operations. These strings are often suspended 3,000 to 10,000 feet (about 850 to 2800 meters), and thus must be able to carry a long term axial stress in excess of about 2500 pounds per square inch (or 2.5 ksi) occasioned during operation and when the pipe string is inserted and removed during the fossil fuel recovery process.

FRP pipe having maximum hoop strength can be designed if the reinforcing fiber is wound at an angle close to 90° to the pipe axis, e.g., +/- 70° up to 90°. Conversely, maximum tensile strength is developed where the reinforcing fiber is applied at an angle close to 0° to the pipe axis, e.g. +/- 30° down to 0°. However, pipe wound at or close to 90° exhibits sever diminishment of axial tensile strength while pipe wound at or close to 0° exhibits severe diminishment of hoop strength. Pipe wound at intermediate pipe axis angles between +/- 30° to +/-

70° (as disclosed in U.S. Patent 2,843,153) generally compromises hoop and particularly axial strength and may be insufficiently strong for practical use in many fossil fuel recovery operations.

One technique for attempting to maximize both hoop and axial strength is to lay down the reinforcing fiber composite as separate laminate layers one atop another, each layer having the fibers disposed at different pipe axial angles designed to maximize the hoop or axial stress bearing properties of the pipe as well as minimize the coefficient of expansion of the composite pipe. An example of such a construction containing +/- 20° to +/- 60° fiber layers alternating with 90° layers is disclosed in U.S. Patent 5,330,807. Other similar layered laminates are disclosed in U.S. Patents 4,728,224 and 4,385,644.

Laminates of this type comprising a plurality, e.g., 3 to 9, separate layers are generally designed for an optimization of hoop or axial stiffness and therefore do not take advantage of the anisotropy of unidirectional fiber composites. For instance, alternating a 0 and +/- 70 degree lay-up does not take advantage of the maximum hoop strength of the +/- 70 degree layer or the maximum axial strength of the 0 degree layer.

Also, composite laminates currently commercially available exhibit a serious deficiency which makes their use not cost effective in applications that generate even moderate pipe stress levels. Microcracking and delamination of the pipe wall structure at or near the pipe joints and/or along the pipe length provide a leak path for fluids, commonly referred to as "weeping", which can occur at fluid pressures which can be 5 to 10 times less than the pipe short-term burst pressure. Intrusion of water into the pipe wall structure via these microcracks can attack glass fiber surfaces and/or binder resin, leading to delamination and premature pipe failure.

Although microcracking can be mitigated by increasing the pipe wall thickness, this solution drives the composite pipe and tubing cost up as compared to that of carbon steel. The higher cost constitutes a barrier to the substitution of composite pipes and tubing for carbon steel in moderate to high (injection) pressure applications. Also, in downhole applications, the increased wall thickness prevents the use of composites where the diameter of the well bore is constrained, because of the cross-sectional area available for fluids to flow is smaller than that of carbon steel. The use of composites in these applications would require drill holes with larger diameter, and this gives rise to additional drilling costs.

The axial strength of composite pipe cannot be significantly increased by increasing the wall thickness. This limits composite downhole tubing, casing, and injection tubing to wells whose depth does not exceed about 5000 ft.

Accordingly, it is a primary object of this invention to provide layered composite FRP piping having acceptable hoop and axial strength which is more resistant to microcracking and delamination on the one hand and also has diminished wall thickness on the other hand such that the piping is compatible with carbon steel well bore/casing dimensions.

SUMMARY OF THE INVENTION

The present invention provides a composite fiber reinforced plastic pipe comprising an elongated hollow tubular body having a wall structure formed from a plurality of layers of continuous reinforcing fibers fixed in a resin binder, each fiber layer containing fibers oriented at an angle with respect to the longitudinal axis of the pipe, said pipe including an outer axial load-bearing layer containing said fibers disposed at an angle of 0 up to +/- 30° with respect to said longitudinal pipe axis, said outer layer in fixed contact with a second layer

disposed radially inward of said outer layer and containing said fibers disposed at an angle of greater than +/- 30° with respect to said longitudinal pipe axis.

The pipe is designed so that when male threaded joint sections are molded or cut at the outer wall surface of one or both ends of the pipe, the molded/cut threads extend into/onto the axial load bearing layer of the pipe such that this layer carries substantially all of the axial stress generated during the mechanics of fossil fuel recovery. This reduces the shear stress and axial strain mismatch between the axial load bearing layer and adjacent layer(s) which are designed to maximize the hoop strength of the pipe.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is an elevation view in partial section of the composite pipe element of this invention.

Figures 2 and 3 are schematic cross sectional views of the wall section of two different commercial composite pipes having a plurality of layers having alternating fiber orientations.

Figure 4 is a schematic cross sectional view of the wall section of a two layer composite pipe wherein the fiber orientations in each layer are in accordance with this invention.

DETAILED DESCRIPTION OF THE INVENTION

Referring to the drawings, Figure 1 shows an elevational view in partial section of a male threaded end section of pipe constructed in accordance with an embodiment of this invention. As shown, the pipe consists of an elongated hollow tubular body 1 constructed of three laminated fiber reinforced polymer

layers shown at 2, 3 and 4 respectively and an optional fourth protective or wrapping layer shown at 5. The end section of the pipe shown at 6 comprises a male threaded tapered joint section cut or molded into outer reinforced layer 4. Reinforcing fibers shown forming helical patterns at 2 and 3 and a horizontal pattern at 4 are drawn to illustrate fiber winding patterns and are not drawn to scale to show fiber winding density.

Layer 4 of Figure 1 is the axial load bearing layer of the pipe and is designed to bear substantially all of the axial load exerted on the pipe when a number of pipe segments are coupled to form a string and the string is disposed either horizontally (i.e., above or below ground) or vertically (i.e., under water and/or into well bores). Axial load is transmitted along layer 4 through female threaded connectors or couplers (not shown) which are adapted to mate with two pipe ends which are to be joined during the construction of a pipe string. The taper and cut of male threaded joint section 6 extends into axial load bearing layer 4, preferably to a degree short of reaching underlying layer 3.

The fibers present in binder layer 4 are disposed at an angle with respect to the longitudinal pipe axis designed to maximize the axial tensile load bearing properties of this layer, e.g., at an angle ranging from 0° up to +/- 30°, more preferably up to about +/- 15° and most preferably at about 0°. Fibers at 4 in Figure 1 are shown disposed at a 0° angle with respect to the pipe axis, but it is understood that this angle may vary up to and including +/- 30°.

Layer 3 shown in Figure 1 is a hoop load bearing layer of the pipe and comprises a second layer in fixed contact with layer 4 and is disposed radially inward of layer 4. The reinforcing fibers present in layer 3 are disposed at an angle of greater than +/- 30° with respect to the longitudinal pipe axis, more preferably greater than +/- 40° and up to 90° with respect to the pipe axis. Where layer 3 is

the sole hoop load bearing layer, the fibers are preferably disposed at an angle of at least +/- 55°, more preferably about +/- 70°, with respect to the pipe axis.

Layer 3 shown in Figure 1 may be the sole hoop load bearing layer or hoop stress may be further accommodated by one or more optional additional layers such as layer 2, which is disposed radially inward of layer 3 and in fixed contact therewith. Layer 2 contains reinforcing fibers disposed preferably at an angle greater than the angle of disposition of the fibers in layer 3 and up to an angle of 90° with respect to the longitudinal pipe axis. Most preferably the fibers in layer 2 are disposed at an angle of at least +/- 60° with respect to the pipe axis.

In a preferred embodiment of the invention where the pipe comprises three composite reinforcing layers, the fibers in layer 4 are disposed at an angle of about 0°, the fibers in layer 3 are disposed at an angle of +/- 40° to +/- 60° and preferably about +/- 55°, and the fibers in layer 2 are disposed at an angle of greater than +/- 60°, preferably about +/- 70°, each with respect to the longitudinal pipe axis.

Layer 5 shown in Figure 1 is an optional layer which may be applied as a protective layer or as a fiber reinforced winding layer to insure that the fibers in layer 4 are tightly bound in the resin binder. Layer 5 is not designed as an axial load bearing layer and is cut away at the pipe ends prior to forming the tapered male threaded joint section 6.

Composite laminate pipes of this invention are made by the well known wet filament winding process such as disclosed in the aforementioned U.S. Patent 2,843,153. By this method, a bundle of continuous reinforcing filaments is impregnated with a fluid resin material, preferably an uncured thermosetting resin, and fed under tension through a shuttle which traverses back and forth over a

rotating mandrel. Alternatively, the rotating mandrel itself may traverse back and forth and the shuttle may be in a fixed position.

The impregnated fiber bundles are built up along the mandrel in close proximity or abutting one another and form criss cross (helical) patterns as they are built up one layer atop another until the desired layer thickness is achieved. The angle of disposition of the fibers with respect to the mandrel longitudinal axis may be largely controlled as a function of the lateral speed of the shuttle as it traverses the mandrel. After the desired thickness of the initial layer is achieved (layer 2 in Fig. 1), the process is adjusted to lay down a second layer of resin impregnated fibers at an angle different than that of layer 2 (layer 3 in Fig. 1), and so on. Axial load bearing layer 4 may also be applied using the filament winding technique except where the fibers are disposed at an angle of 0° with respect to the mandrel axis. In this latter case, the axial load bearing layer of desired thickness is applied as a resin saturated prepeg tape or sleeve which can be laid up by hand. Alternatively, the longitudinal lay down method may be used where 0° fibers are laid on the mandrel atop layer 3 while being captured by a 90° outer wrap, such as illustrated at 5 in Figure 1.

The resinous material which serves as a binder for the reinforcing fibers is preferably a thermoset resin such as an epoxy. The preferred epoxy resins for carrying out the invention include bishpenol - A diglycidyl ester, bisphenol glycidyl ether, novolac resin glycidyl ether and aliphatic polyepoxide, though other suitable epoxy resins may be used. Aside from epoxy resins, other suitable thermosetting polymers include phenolic resins, unsaturated polyesters and polyimides. The degree of condensation of these resins is selected so that the viscosity of the resin product is adapted to the working conditions necessary for formation of the tubular body. The thermosetting polymers are mixed with suitable hardeners, such as aromatic polyamines, polyamides, aliphatic polyamines, polyacids, polyanhydrides, dicyandiamides, primary or secondary amines, mixtures

of these, or any other of the hardeners typically used as crosslinking agents for thermosetting resins.

The quantity of resin applied to the fibers in forming the tubular pipe body should be sufficient such that the volume fraction of fiber present in the cured product is at least about 40%, more preferably in the range of about 50 to 70%, still more preferably about 55 to 65%, with the balance being the epoxy resin composition.

The reinforcing filaments or filament bundles may comprise continuous filaments of glass, graphite, aramide or Kevlar® fiber, or a combination of these fibers, which exhibit extremely high tensile strength. The diameter of these filaments may range from about 5 to 20 microns, more preferably from about 7 to 16 microns. The glass fibers are preferably surface coated with a material, e.g., an aminopolysiloxane, which enhances the wettability and adhesion of the fiber surface with respect to the resin binder.

After the resin-wetted composite pipe is assembled on the mandrel, the resin is cured by heating the structure to a temperature sufficient to cure the resin, e.g., 100° - 170°C, for a period of time ranging from about 30 minutes up to 12 hours, after which the assembly is removed from the mandrel.

Referring back to Figure 1, the relative thickness of the axial load bearing layer 4 should be sufficient to carry the anticipated long service axial stress on the pipe, (e.g., at least 20 ksi). As a general rule, the axial load bearing layer will comprise 50% or less of the pipe wall thickness, most preferably from about 20 up to 50% of the pipe wall thickness.

The balance of the pipe wall comprises hoop load bearing layer 3 or layers 3 and 2. The hoop load bearing layer(s) are capable of bearing long term

hoop stress in excess of about 20 ksi and are preferably configured such that these layers are also capable of bearing a minimal axial stress of about 4 ksi.

FRP pipe made in accordance with this invention may have outside diameters in the range of about 2 to 36 inches, and are normally used for oil/gas production and transmission. Pipes used for downhole applications fall into two categories: tubing, with an outside diameter of 4.5 inches (nominal) and less; and casing, with an outside diameter greater than 4.5 inches (nominal).

As stated above, FRP pipe constructed in accordance with this invention provide a built-in modality for handling the axial stress and hoop stress forces separately along the pipe wall cross section. This allows for a reduction in pipe wall thickness while at the same time achieving an increase in both hoop strength and axial strength of up to 100%.

For example, Figure 2 shows in cross section a commercially available tubing, 2,000 psig rated, having an outside radius of 1.37 inch and an inside radius of 0.97 inch and a wall thickness of 0.4 inch. The wall consists from inside to outside of five alternating layers containing +/- 70° wound fiberglass fibers surrounding four thinner alternating layers containing 0° disposed fiberglass fibers.

Figure 4 shows a cross section of a similar pipe made in accordance with this invention, but having a wall thickness of only 0.25 inch and containing, from inside to outside a single +/- 70° would fiberglass layer having a thickness of 0.15 inch and single axial load bearing layer containing 0° disposed fiberglass fibers having a thickness of 0.10 inch. The fiber volume fraction in each case is about 60% in each layer.

Comparative tensile and hoop stress evaluation of each pipe configuration demonstrates that the configuration in Figure 4 provides about a 60% increase in hoop strength and about a 70% increase in axial strength as compared with the commercial design of Figure 2. This means that the tubing is not only 60-70% more cost effective but also that it can reach depths about 60-70% of greater than the 5000 foot depth achieved by current commercial tubing.

Yet another advantage afforded by piping configured in accordance with this invention is a reduction in axial strain mismatch between the various layers because the primary layer bearing the axial stress is a single outside layer. Axial load is experienced as a shear load across the cross section of the pipe wall, resulting in an axial strain (deformation). Axial strain throughout the cross section of the pipe wall can lead to delamination and microcracking of the pipe wall over a period of time resulting in the phenomenon known as weeping and premature pipe failure.

Axial strain mismatch for two commercial multilayer pipe configurations is illustrated in Figures 2 and 3, and axial load on the pipe, applied through the pipe connections (shown schematically), is also illustrated. The Figures clearly demonstrate the strain on the outside layers bearing the direct tensile load and additional strain at interfaces of the various layers.

Figure 4 demonstrates the reduction in axial strain mismatch afforded by the pipe design of this invention wherein substantially all of the axial load is supported by the 0° outside layer.

CLAIMS:

1. A composite fiber reinforced plastic pipe comprising an elongated hollow tubular body having a wall structure formed from a plurality of layers of continuous reinforcing fibers fixed in a resin binder, each fiber layer containing fibers oriented at an angle with respect to the longitudinal axis of the pipe, said pipe including an outer axial load-bearing layer containing said fibers disposed at an angle of 0° up to +/- 30° with respect to said longitudinal pipe axis, said outer layer in fixed contact with a second layer disposed radially inward of said outer layer and containing said fibers disposed at an angle of greater than +/- 30° with respect to said longitudinal pipe axis.

2. The pipe of claim 1 wherein the fibers in said axial load bearing layer are disposed at an angle of less than about +/- 15° with respect to said longitudinal pipe axis.

3. The pipe of claim 1 wherein the fibers in said load bearing layer are disposed at an angle of about 0° with respect to said longitudinal pipe axis.

4. The pipe of claim 1 wherein said axial load bearing layer comprises 50% or less of said pipe wall thickness.

5. The pipe of claim 1 wherein the fibers in said second layer are disposed at an angle of greater than about +/- 40° up to 90° with respect to said longitudinal pipe axis.

6. The pipe of claim 5 wherein the fibers in said second layer are disposed at an angle of greater than about +/- 55° with respect to said longitudinal pipe axis.

7. The pipe of claim 1 comprising a third layer disposed radially inward of and in fixed contact with said second layer and containing said fibers disposed at an angle greater than the angle of disposition of said fibers in said second layer and up to an angle of 90°.

8. The pipe of claim 7 wherein the fibers in said second layer are disposed at an angle of greater than about +/- 40° up to about +/- 60° with respect to said longitudinal pipe axis and the fibers in said third layer are disposed at an angle of greater than about +/- 60° up to 90° with respect to said longitudinal pipe axis.

9. The pipe of claim 1 wherein said resin binder is a thermoset resin.

10. The pipe of claim 1 wherein said thermoset resin is an epoxy resin.

11. The pipe of claim 1 wherein said continuous reinforcing fibers are glass fibers.

12. The pipe of claim 1 wherein said fibers comprise at least about 60% of the volume fraction of said pipe wall.

13. The pipe of claim 3 wherein the fibers in said inner layer are disposed at an angle of about +/- 50 to +/- 75° with respect to said longitudinal pipe axis.

14. The pipe of claim 7 wherein the fibers in said axial load bearing layer are disposed at an angle of about 0°, the fibers in said second layer are disposed at an angle of +/- 40° to +/- 60° and the fibers in said third layer are

disposed at an angle of greater than +/- 60° up to 90°, each with respect to said longitudinal pipe axis.

15. The pipe of claim 14 wherein the fibers of said second layer are disposed at an angle of about +/- 55° and the fibers of said third layer are disposed at an angle of about +/- 70°, each with respect to said longitudinal pipe axis.

16. The pipe of claim 1 containing a male threaded joint section cut or molded at the outer wall surface of one or both ends of said pipe, said thread cuts extending into the axial load bearing layer of said pipe.

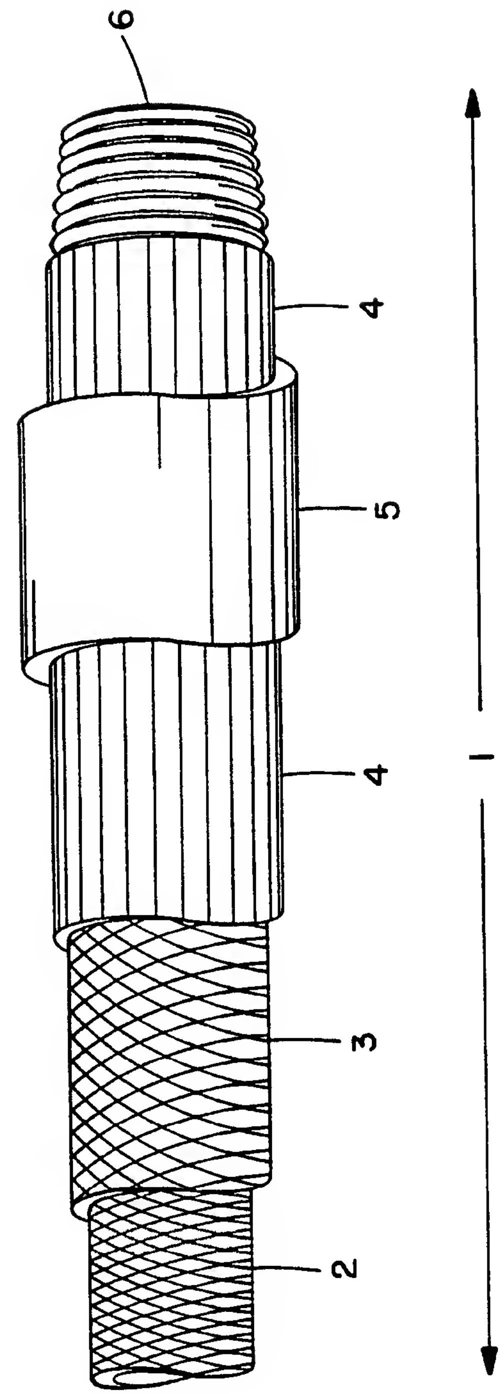
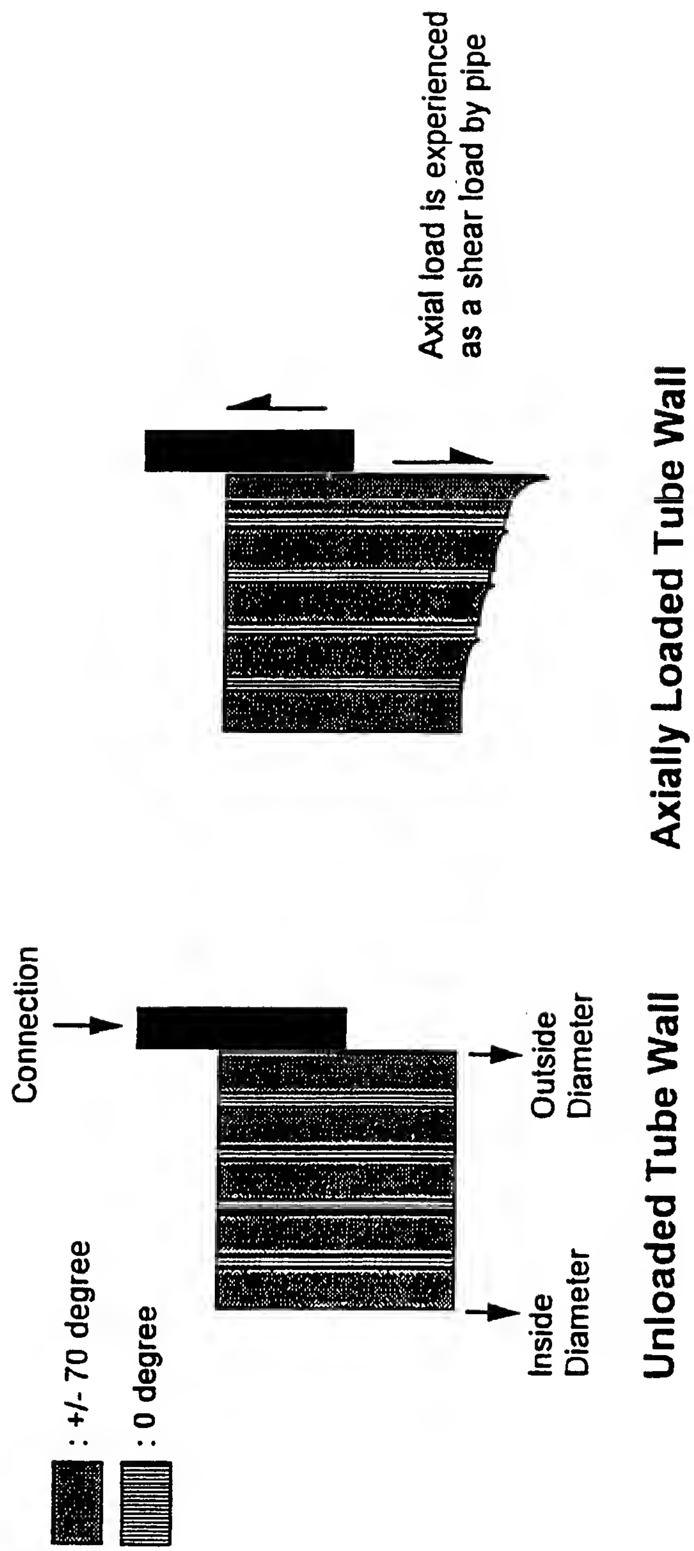


FIG. 1.



Axial load is experienced as a shear load by pipe
Axially Loaded Tube Wall
Connection
: +/- 70 degree
: 0 degree
Outside Diameter
Inside Diameter
Unloaded Tube Wall

Fig. 2

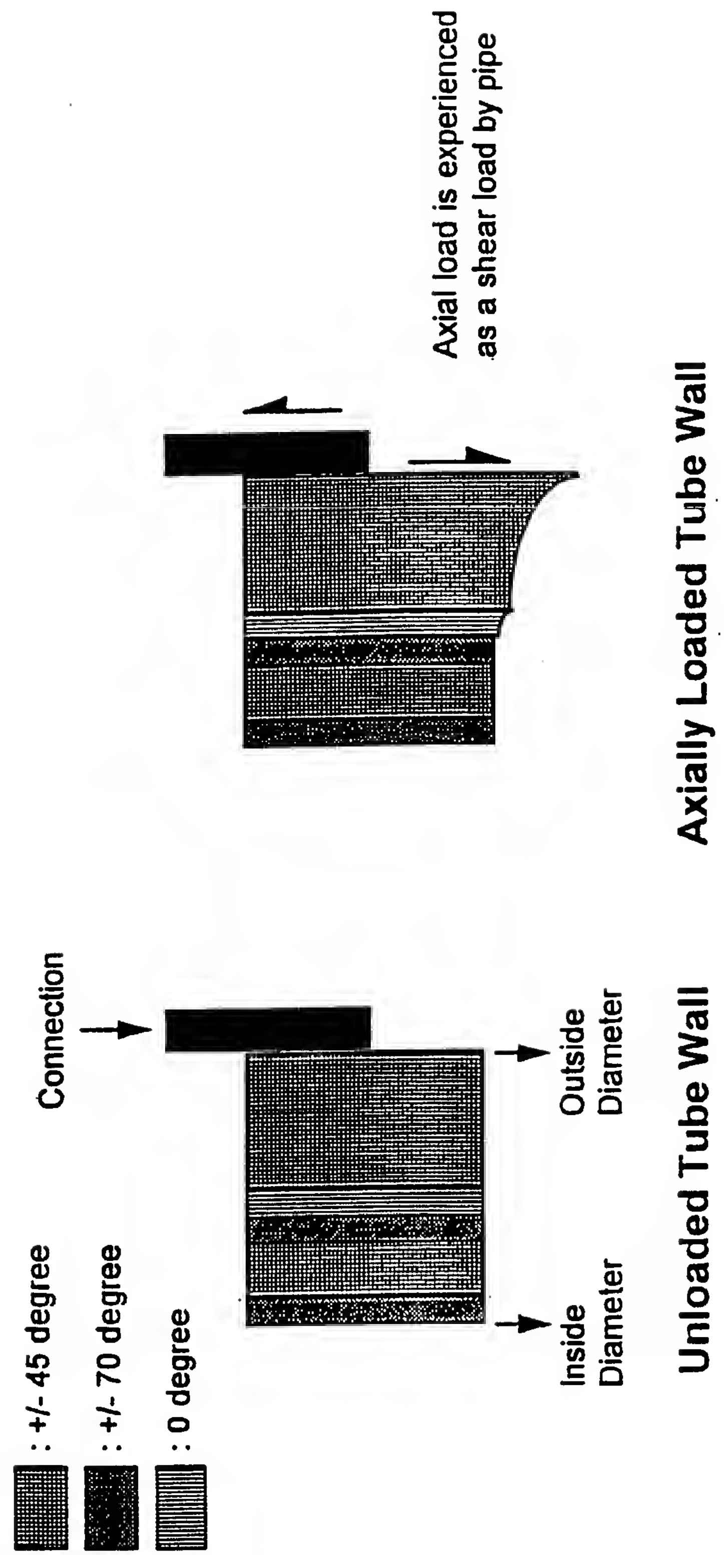

: +/- 45 degree
: +/- 70 degree
: 0 degree
Connection
Outside Diameter
Inside Diameter
Unloaded Tube Wall
Axial load is experienced as a shear load by pipe
Axially Loaded Tube Wall

Fig. 3

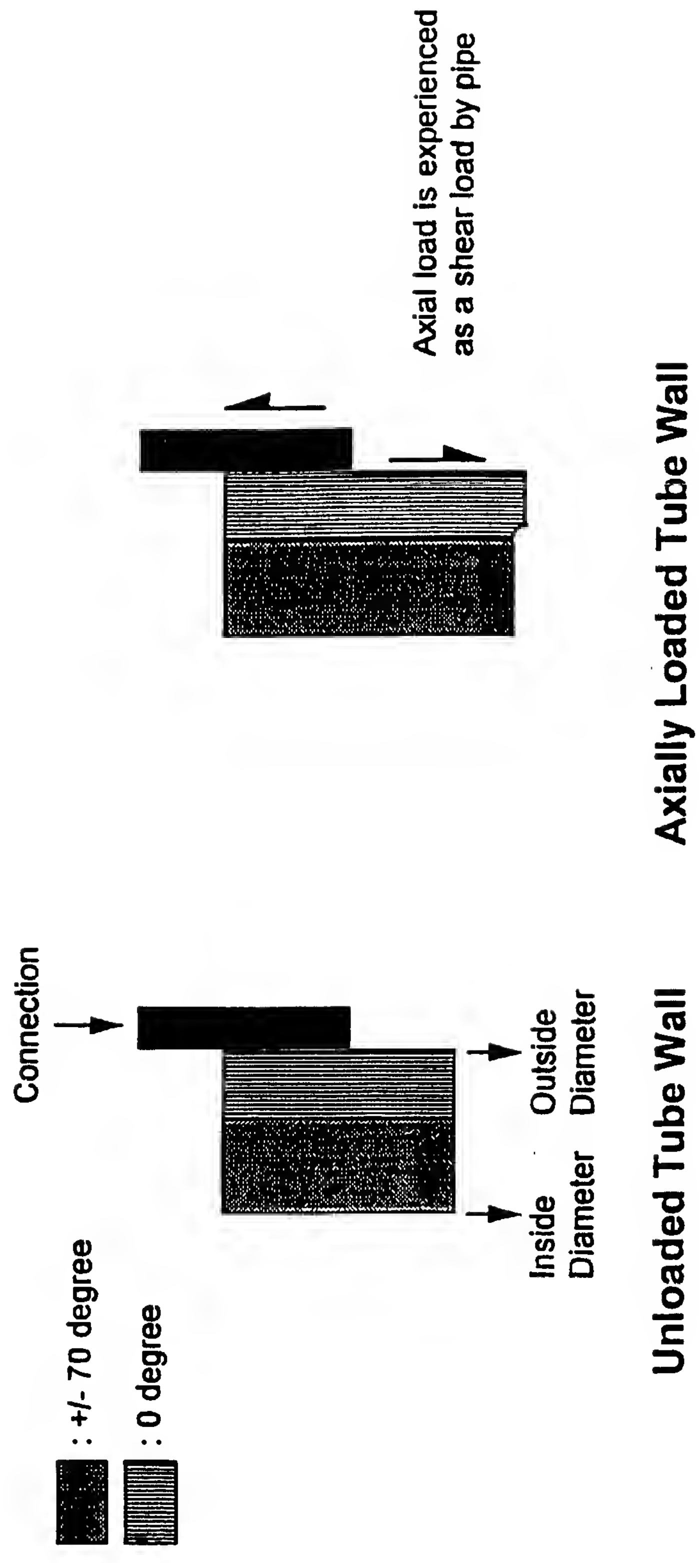

: +/- 70 degree
: 0 degree
Connection
Inside Diameter
Outside Diameter
Unloaded Tube Wall
Axial load is experienced as a shear load by pipe
Axially Loaded Tube Wall

Fig. 4

INTERNATIONAL SEARCH REPORT

Intern   al Application No
PCT/US 98/06458

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 F16L11/08 E21B17/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 F16L E21B B29C D07B E02B B63B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 024 512 A (EATON CORP) 11 March 1981 see abstract see claim 1 see figure 3 ---	1-16
A	US 4 175 992 A (GRAWEY CHARLES E) 27 November 1979 see abstract see figure 5 see column 2, line 13 - line 47 see claims 1-4 ---	1,2,5-8
A	GB 2 165 331 A (EATON CORP) 9 April 1986 see abstract see figure 3 see claim 1 --- -/--	1

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
4 June 1998	22/06/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Schaeffler, C

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INTERNATIONAL SEARCH REPORT

Interr.   ial Application No
PCT/US 98/06458

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication,where appropriate, of the relevent passagee	Relevent to claim No.
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